Quasi-Periodic Oscillations of ∼15 minutes in the Optical Light Curve of the BL Lac S5 0716+714

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ABSTRACT

Over the course of three hours on 27 December 2008 we obtained optical (R-band) observations of the blazar S5 0716+714 at a very fast cadence of 10 s. Using several different techniques we find fluctuations with an approximately 15-minute quasi-period to be present in the first portion of that data at a $> 3\sigma$ confidence level. This is the fastest QPO that has been claimed to be observed in any blazar at any wavelength. While this data is insufficient to strongly constrain models for such fluctuations, the presence of such a short timescale when the source is not in a very low state seems to favor the action of turbulence behind a shock in the blazar's relativistic jet.

Subject headings: galaxies: active – BL Lacertae objects: individual: S5 0716+714 – galaxies: photometry

1. Introduction

Characteristic timescales of variability provide an important way to probe the sub-parsec scale central engines in active galactic nuclei (AGN) by providing information about the sizes and locations of emission regions. In blazars, i.e., BL Lacertae objects (BL Lacs) and flat spectrum radio quasars (FSRQs), Doppler boosted emission from a relativistic jet has long been recognized to provide the only feasible explanation for their non-thermal spectra and radio morphologies on small-scales (e.g., Blandford & Rees 1978; Urry & Padovani 1995). Still, the question of just where emission at different frequencies originates remains

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somewhat uncertain (e.g., Marscher et al. 2008). Rapid fluctuations have long been known to characterize blazars, with the prototype, BL Lac, seen to flicker over just a few minutes in early single channel photometry with 15-second temporal resolution (Racine 1970).

The bright, high declination BL Lac, S5 0716+714, at redshift $z = 0.31 \pm 0.08$ (Nilsson et al. 2008) has been extensively studied across the electromagnetic spectrum and exhibits strong variability on a wide range of timescales, ranging from minutes to years (e.g., Gupta et al. 2008a,b, 2009, and references therein). The optical duty cycle of S5 0716+714 is nearly unity, indicating that the source is always in an active state in the visible (Wagner & Witzel 1995). This blazar was recently shown to be a strong source in the high energy gamma-ray band by Fermi-LAT (Abdo et al. 2009).

There is good evidence for the presence of quasi-periodic oscillations (QPOs) in the emission of just a few blazars (Espaillat et al. 2008; Gupta et al. 2009; Rani et al. 2009; Lachowicz et al. 2009). The blazar S5 0716+714 is among these rare exceptions: a possible QPO on the timescale of $\sim$1 day may have been observed simultaneously in an optical and a radio band (Quirrenbach et al. 1991). On another occasion, quasi-periodicity with a time scale of $\sim$4 days appeared to be present in its optical emission (Heidt & Wagner 1996). Five major optical outbursts between 1995 and 2007 have occurred at intervals of $\sim 3.0 \pm 0.3$ years (e.g., Raiteri et al. 2003; Gupta et al. 2008a, and references therein). Recently, Gupta et al. (2009) used a wavelet analysis on the 20 best nights of over 100 nights of high quality optical data taken by Montagni et al. (2006), and found high probabilities that S5 0716+714 showed quasi-periodic components to its variations on several nights that ranged between $\sim$25 and $\sim$73 minutes.

Among the other blazars, PKS 2155$-$304 possibly showed a quasi-periodicity around 0.7 days during 5 days of observations at UV and optical wavelengths (Urry et al. 1993). Very recently, somewhat better evidence for a QPO of $\sim$4.6 h in the XMM-Newton X-ray light curve of PKS 2155$-$304 has been reported by Lachowicz et al. (2009). An XMM-Newton light curve of the quasar 3C 273 appears to have a quasi-periodic component with a timescale of about 3.3 ks (Espaillat et al. 2008). Using the $\sim$13 year long data taken by the All Sky Monitor on the Rossi X-ray Timing Explorer satellite, Rani et al. (2009) reported good evidence of nearly periodic variations of $\sim$ 17.7 days in the blazar AO 0235+164 and $\sim$ 420 days in the blazar 1ES 2321+419. The narrow line Seyfert 1 galaxy, RE J1034+396, while not a blazar, strongly indicated the presence of a $\sim$1 hour periodicity during a 91 ks observation by the X-ray satellite XMM-Newton (Gierliński et al. 2008).

In this Letter, we exhibit evidence for a QPO of $\sim$15 minutes in a single densely sampled optical light curve of the blazar S5 0716+714. We first used a structure function (SF) analysis to find a hint of such a QPO and we then quantified the strength of this signal using Lomb-

Scargle Periodogram (LSP) and Power Spectral Density (PSD) methods. We find this to be a strong case for the discovery of the shortest nearly periodic variation seen for any blazar, or for that matter, any AGN, in any waveband.

2. Observations and Data Reduction

Our observations of S5 0716+714 were carried out with an Andor EMCCD (Electron Multiplying Charge Coupled Device) camera mounted at the f/13 Cassegrain focus of the 1.2 m telescope operated by the Physical Research Laboratory (PRL) at Gurushikhar, Mt. Abu, India. We observed this source on 23, 27 and 28 December 2008 and 3 January 2009; the total amount of data collected over those four nights was 9.6 hours. The 1k $\times$ 1k EMCCD has square pixels with sides of 13 μm size. With electron multiplication technology, the read noise in the system is expected to be negligible compared to normal CCD cameras (Mackay et al. 2001) and the performance approaches near photon counting efficiency. The camera was thermoelectrically cooled to -80 C$^{\circ}$ for our observations and had negligible dark current. An R filter and a temporal resolution of only 10 seconds were employed. The typical seeing was $\sim$1.6 arcsec. On each night, we took several bias frames and twilight sky flats in the R band. To improve the S/N ratio, we performed these observations in 2 pixel $\times$ 2 pixel binning mode so that 4 pixels work as a single super-pixel.

The image pre-processing was done using the standard routines in Image Reduction and Analysis Facility[1] (IRAF) software. Data analysis, or processing of the data, involved performing aperture photometry using Dominion Astronomical Observatory Photometry (DAOPHOT II) software (Stetson 1992). We first carried out aperture photometry with four different aperture radii, i.e., 1$\times$FWHM, 2$\times$FWHM, 3$\times$FWHM and 4$\times$FWHM. We discovered that aperture radii of 3$\times$FWHM usually provided the best S/N ratio and we adopted it for our work. The standard stars 8 and 11 (González-Pérez et al. 2001) whose apparent brightnesses were close to that of the source and were always observed in the same field as the blazar were used to check that the variability was intrinsic to the blazar. The standard star 11 was used to calibrate the blazar's magnitude. Only on the night of 27 December 2008 did we detect interesting rapid variability and that light curve is displayed in Fig. 1. We note that over the past 15 years S5 0716+714 has varied between $\sim$ 12.3 and $\sim$ 15.6

[1]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

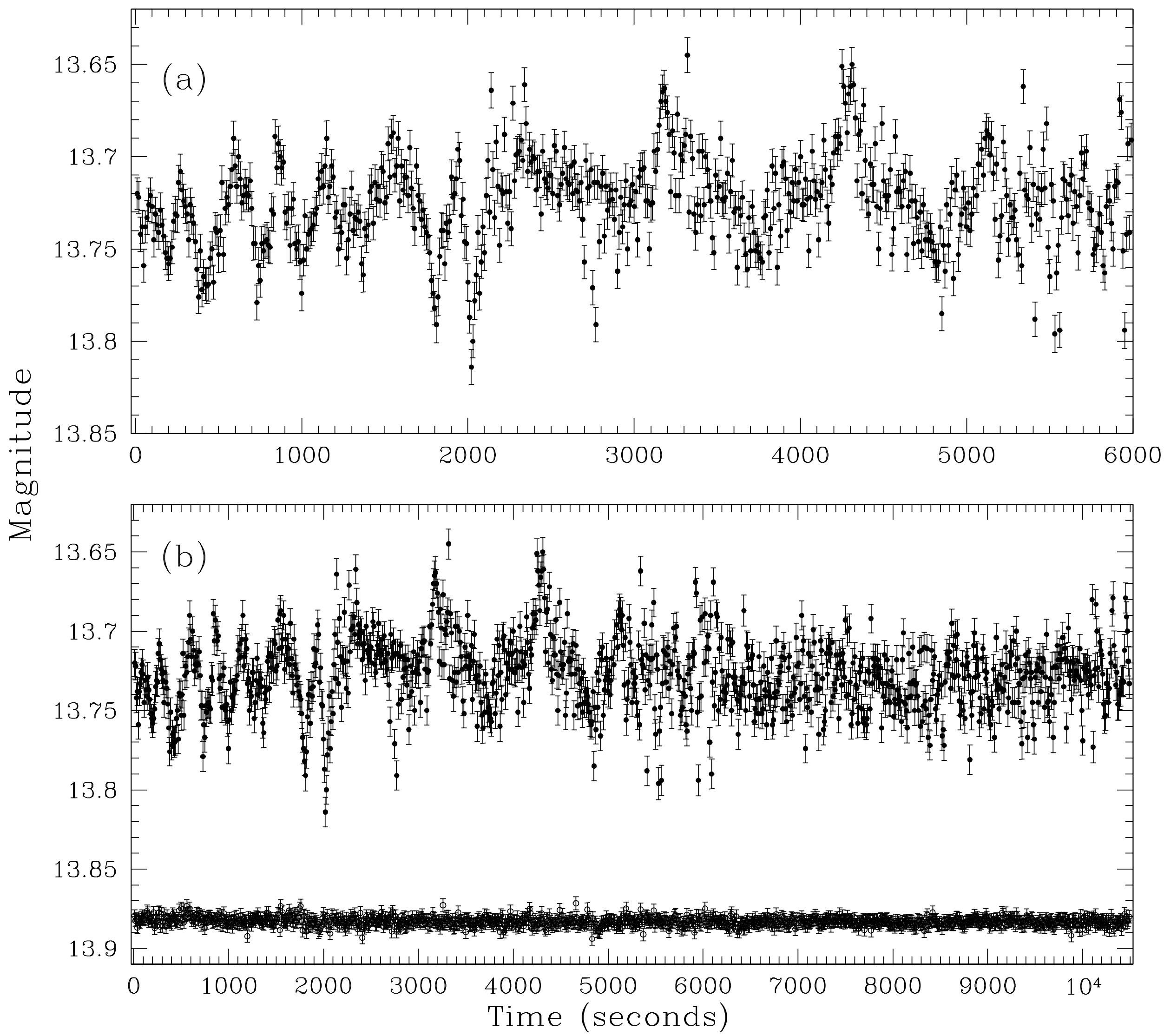

Fig. 1.— (a) The R passband light curve of the blazar S5 0716+714 in the first 1.66 hours of observations; the temporal origin is at 18.86976 hrs UT on December 27, 2008. (b) The calibrated light curve of the source for the entire observation, along with the differential instrumental magnitudes of standard stars 8 and 11, offset by 14.14 mag.

R-band magnitudes, though it was even fainter earlier (Raiteri et al. 2003; Nesci et al. 2005; Gupta et al. 2008a).

3. Analysis and Results

In order to be certain the apparent variability of S5 0716+714 is significant we used the F-test, shown by de Diego (2010) to be superior to commonly used methods. The F-statistic is the ratio of the sample variances, or $F = s_Q^2/s_S^2$, where the variance for the quasar differential light curve is s_Q^2, while that for the standard star is s_S^2. We used the F-test code available in R[2] and find $F = 18.3748$, with a significance level of 0.9999998, or $> 5\sigma$.

We have also calculated the variability amplitude parameter, A (Heidt & Wagner 1996), to see the percentage variation in the light curve of source. For S5 0716+714 we find $A = 16.9\%$. The calculated fractional rms variability amplitude for the LC (Vaughan et al. 2003) is $F_{var} = 15.45$.

A visual inspection of the light curve for the first two hours shown in Fig. 1(a) indicates a possible periodic modulation of the variability at about 900 s, along with a hint of even faster modulations at the very beginning of the observation. The calibrated light curve for the entire 3 hours of measurements taken at a 10 s cadence, along with the differential instrumental magnitudes of standard stars 8 and 11, are displayed in Fig. 1(b). The light curve averaged over 30 s intervals folded at a putative period of 900 s is Fig. 2(a).

3.1. Structure Function

The first order structure function (SF) is a simple way to search for periodicities and timescales of variability in time series data trains (e.g., Simonetti et al. 1985). Here we give only a very brief summary of the method; for details refer to Rani et al. (2009). The first order SF for a data train, a, is defined as

$$D_a^1(k) = \frac{1}{N_a^1(k)} \sum_{i=1}^{N} w(i)w(i+k)[a(i+k) - a(i)]^2, \tag{1}$$

where k is the time lag, $N_a^1(k) = \sum w(i)w(i+k)$, and the weighting factor, $w(i)$, is 1 if a measurement exists for the i^{th} interval, and 0 otherwise. For a time series containing

[2]R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

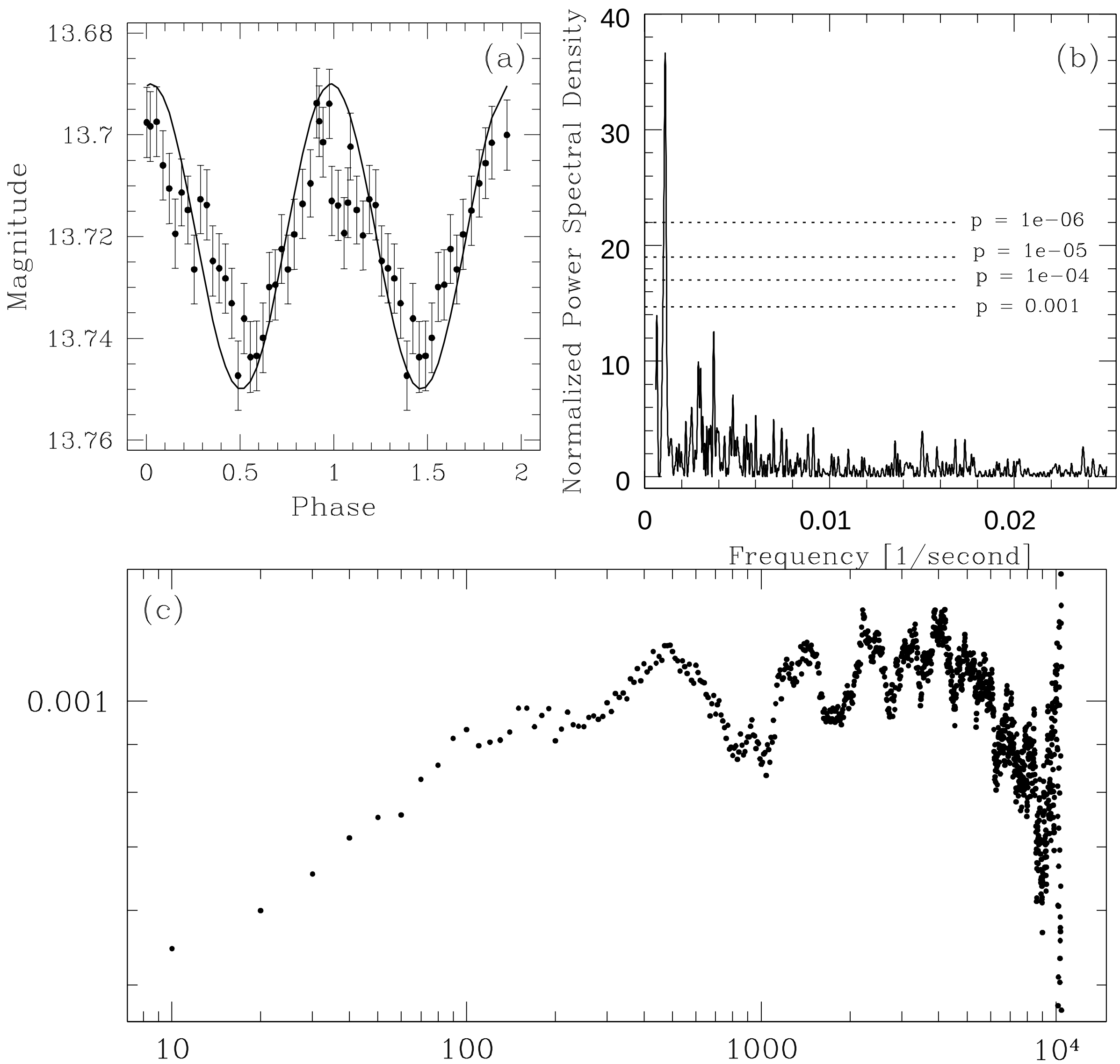

Fig. 2.— (a) Light curve of the source folded at a period of 900 s; (b) LSP analysis showing a peak at a period of 904 s; (c) SF curve of the entire data set showing multiple cycles of ∼927 s.

a periodic pattern, the SF curve shows minima at time lags equal to the period and its subharmonics (e.g., Lachowicz et al. 2006), although dips and wiggles in SFs are not always reliable indicators of timescales (Emmanoulopoulos et al. 2010). The SF analysis curve of the whole data set is displayed in Fig. 2(c). The first dip and the 7 cycles of its subsequent subharmonics correspond to a possible period of 927±30 seconds.

3.2. Lomb−Scargle Periodogram

The Lomb-Scargle Periodogram (LSP), introduced by Lomb (1976) and extended later by Scargle (1982), is an excellent technique for searching time series, as long as white-noise, $P_N(f) \propto f^0$, is the dominant noise process. Press & Rybicki (1989) provided a more practical mathematical formulation. For the for details of method and formulae see Rani et al. (2009) and references therein.

We used an online available R-language code for the LSP[3]. The LSP analysis of the whole data set is displayed in Fig. 2(b). The LSP analysis revealed the detection of significant frequency corresponding to a period of 904 seconds with a significance level of 0.999999977. Two questions usually arise concerning the validity of a periodogram result (Scargle 1982); the first is statistical and the second is spectral leakage. The statistical difficulty is mitigated by the good S/N ratio of ∼35 in our case. Spectral leakage, which is also known as aliasing, involves the spreading of periodogram power to other frequencies that are actually not present in the data. Since our data is uniformly sampled there might be chances of aliasing. But as essentially the same period is confirmed by SF and PSD analyses the strong signal is very unlikely to arise in this fashion.

However, as LCs of most AGN contain red-noise as well as white-noise, a more robust test is required to quantify the presence of a QPO.

3.3. Power Spectral Density

The power spectral density (PSD) is a powerful tool to search for periodic signals in time series, including those contaminated by white- and/or red-noise (e.g., Vaughan 2005). We employed a PSD analysis method (Vaughan et al. 2003; Vaughan 2005) that is suitable for these types of LCs. First, as shown in Fig. 3, we fit a single power-law (SPL) to the calculated PSD, assuming it to have a form $P(f) \propto f^{\alpha}$ at low frequencies and then examined

[3]http://research.stowers- institute.org/efg/2005/LombScargle

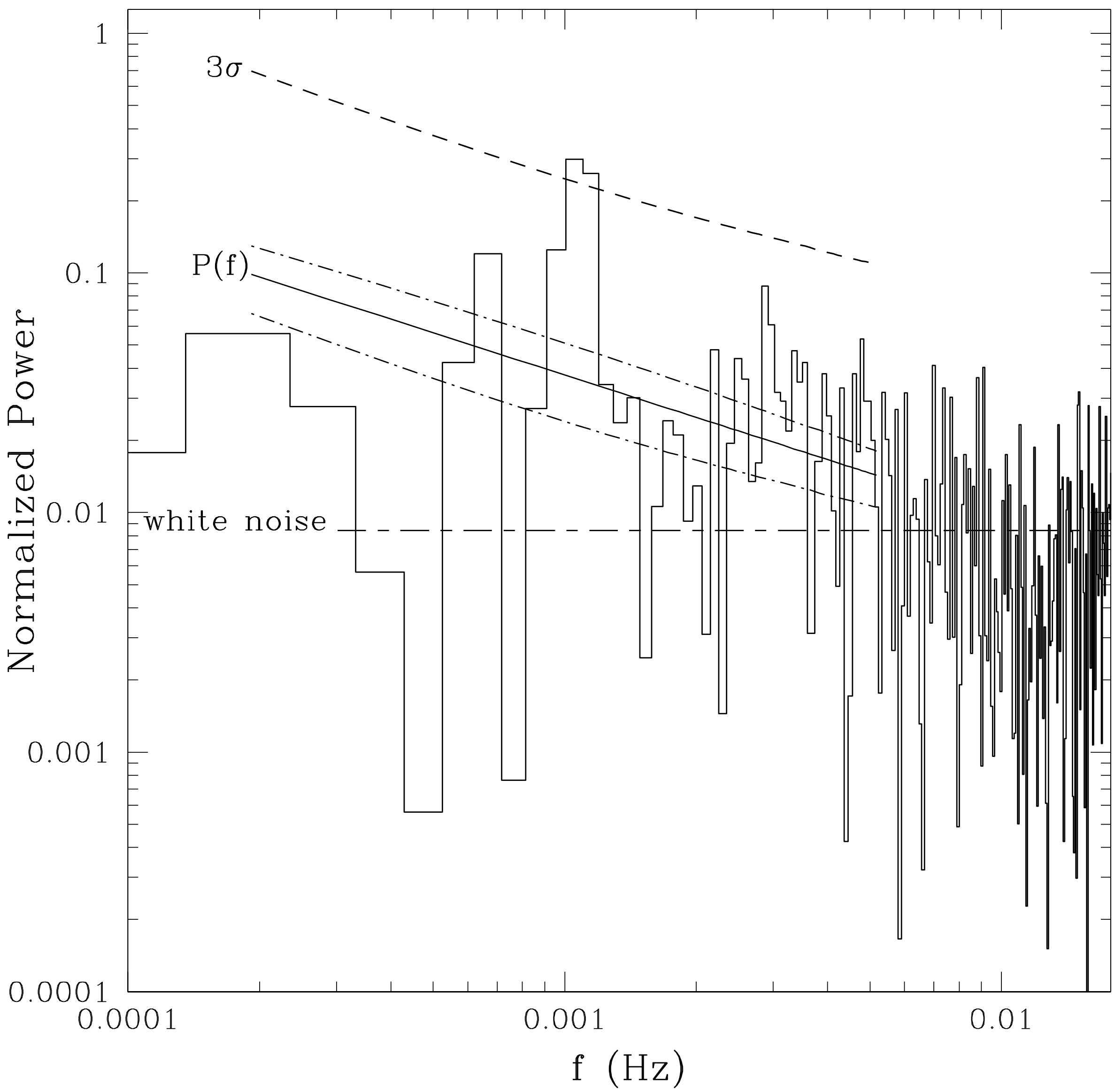

Fig. 3.— PSD of S5 0716+714. $P(f)$ is the best fitting single power law with index -0.58 ± 0.06 (the dot-dashed lines are the calculated uncertainty in the model); a 3σ confidence limit and the white-noise level are shown.

the significance of the frequency peak using the method of Vaughan (2005). This analysis indicates the presence of a QPO signal with peak frequency $\simeq$0.001077 Hz (or period $\simeq$928 s), with a 3.4σ significance level. The calculated significance is global, i.e., corrected for the number of frequencies tested. The range of frequencies used for calculating the global significance of the QPO is $0.0002 \leq f \leq 0.002$ which amounts to 28 frequency bins. This range excludes frequencies that are significantly dominated by white noise.

We next checked the statistical significance of this QPO using Monte Carlo simulations. We generated a series of 10^4 simulated LCs following a given SPL having the same number of bins, mean and variance as the observed LC (Timmer & Koenig 1995) using an IDL code available on-line[4]. The PSD analysis resulting from the simulated LCs using a SPL with the index from the best fit to our data are compatible with the results shown in Fig. 2 and indicate an average significance of 3.2σ. We also considered the alternative null hypothesis of a broken power-law (BPL). The best fitting BPL indices are, respectively, +0.39 and −0.8 above and below the break frequency of $\simeq$ 0.0011Hz. The nominal statistical significance of the QPO frequency in this case is $\sim 3.1\sigma$. Finally, we performed PSD analyses of simulated LCs generated from BPLs and calculated periodograms for each of them, finding that the periodic signal was still significant at 3σ. Hence we conclude that the observed QPO at a frequency of $\sim$0.001077 Hz is statistically significant, irrespective of the assumed model of continuum power.

4. Discussion and Conclusions

This discovery of a nearly periodic signal of $\sim$900 seconds in the optical R passband light curve of the blazar S5 0716+716 adds a unique new point to the variability studies of blazars at intraday timescales. The presence of 7 cycles with a $> 3\sigma$ significance level allows us to make a strong claim for the shortest optical QPO detected so far.

The simplest possible explanation for such a short period might be the flux arising from hot spots or some other non-axisymmetric phenomenon related to the orbital motions that are close to the innermost stable circular orbit around a supermassive black hole (SMBH) (e.g., Zhang & Bao 1991). Adopting $z = 0.31$ for S5 0716+714 (Nilsson et al. 2008), means that a 900 second period at the inner edge of a corotating disk corresponds to a SMBH mass of 1.5 $\times 10^6$ $M_\odot$ for a non-rotating BH and 9.6 $\times 10^6$ $M_\odot$ for a maximally rotating BH (Gupta et al. 2009). If the source arises somewhat further out in the accretion disk, then the BH mass would be even less than these modest values.

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[4]http://astro.uni-tuebingen.de/software/idl/aitlib/timing/timmerlc.html

However, since blazar jets are pointing very close to the line-of-sight of the observer (e.g., Urry & Padovani 1995) the emerging flux, particularly in active phases, is dominated by emission from jets. Turbulence behind a shock propagating down a jet (e.g. Marscher et al. 1992) is a very plausible way to produce dominant eddies whose turnover times can yield short-lived, quasi-periodic fluctuations in emission at different wavelengths. Since Doppler boosting will greatly amplify the very weak intrinsic flux variations produced by small changes in the magnetic field or relativistic electron density, these intrinsically weak fluctuations can be raised to the level at which they can be detected (e.g., Qian et al. 1991). This same Doppler boosting reduces the time-scale at which these fluctuations are observed compared to the time-scale they possess in the emission frame. Although it is difficult to quantify these effects precisely, this mechanism does seem to provide an excellent way to understand the type of short-lived optical intra-night variability with periods of tens of minutes seen here.

It is also possible that QPOs originate from a relativistic shock propagating down a jet that possesses a helical structure, as can be induced by magnetohydrodynamical instabilities (Hardee & Rosen 1999) or even through precession. Indeed, in some cases where radio jets can be resolved transversely using Very Long Baseline Interferometry, edge-brightened and non-axisymmetric structures are seen (e.g., M87, Ly et al. (2007); Mkn 501, Piner et al. (2009)). A relativistic shock propagating down such a perturbed jet will induce significantly increased emission at the locations where the shock intersects with a region of enhanced magnetic field and/or electron density corresponding to such a non-axisymmetric structure. Because Doppler boosting is a sensitive function of viewing angle substantial changes in amplitude of jet emission can be seen by the observer (Camenzind & Krockenberger 1992; Gopal-Krishna & Wiita 1992). Therefore, the observed periodic component in the optical light curve of S5 0716+714 might be attributed to the intersections of a relativistic shock with successive twists of a non-axisymmetric jet structure, though they would have to be surprisingly tight to yield such a short period.

We have analyzed the optical R passband light curve of the well-known BL Lac S5 0716+714 observed on 27 December 2008 with a 10 second cadence that provided the best time resolution so far obtained for a blazar. Different analyses all indicate this light curve contains a periodic component to its fluctuations of about 15 min. Although this particular BL Lac showed earlier evidence of periodic variations in radio through X-ray wavebands ranging from tens of minutes to several years, our new data provides the shortest known quasi-period yet detected in a blazar.

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